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MULTITURN INJECTION INTO ACCUMULATORS FOR HEAVY ION INERTIAL FUSION

C.R. Prior*, H. Schönauer

Abstract

The injection of heavy ions into high current rings is complicated because it is impossible to use charge exchange in material foils to produce the singly charged heavy ions needed to keep space charge manageable on the one hand, and because losses need to be rigorously restricted to < 1 % on the other.
With these constraints, the number of turns that may be injected by conventional multiturn injection is limited. This paper describes how the number may be increased by a two-dimensional technique of painting Lissajous-like patterns in *x-y* space, using an inclined or a corner septum. Simulation examples are presented showing the nature of the beam created in the accumulator and the likely effects of space charge forces.

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Abstract

The injection of heavy ions into high current rings is complicated because it is impossible to use charge exchange in material foils to produce the singly charged heavy ions needed to keep space charge manageable on the one hand, and because losses need to be rigorously restricted to $\leq 1\%$ on the other.

With these constraints, the number of turns that may be injected by conventional multiturn injection is limited. This paper describes how the number may be increased by a two-dimensional technique of painting Lissajous-like patterns in x–y space, using an inclined or a corner septum. Simulation examples are presented showing the nature of the beam created in the accumulator and the likely effects of space charge forces.

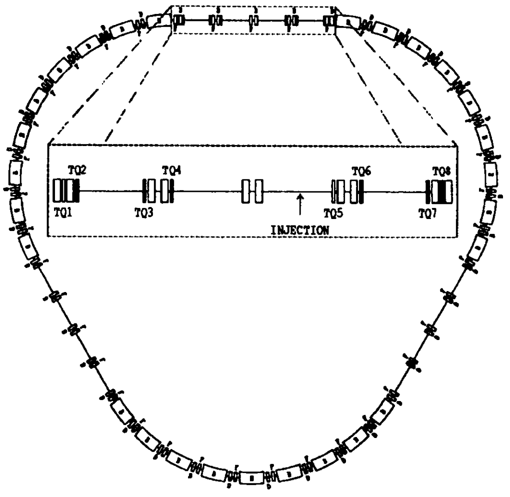

Figure 1: Model accumulator ring for 20 turn transverse injection

1 INTRODUCTION

In the scenarios of a Heavy Ion Driven Inertial Fusion plant (HIDIF) studied to date, singly charged ions from a high current linac are multiturn injected into a number of storage rings before being compressed and merged in the transport to a final focus. At present, a test facility for 10 GeV beam energy delivering 3 MJ within 5 ns to the target is under study [1]. Since the 0.4 A linac pulse in this scenario has a length of the order of 100 km, it is clear that the maximum number of turns that may be injected into each storage ring has a crucial impact on the total circumference and thus on the size and cost of the facility. The injection of 15 or more turns has been attained in synchrotrons for decades now; however, efficiencies achieved do not exceed 60%. In order to inject a comparable number of turns with $\leq 1\%$ loss, both transverse dimensions have to be explored. The starting point is the Lissajous pattern of the injected turns in the x–y plane, which is optimised by varying fractional tunes, programming closed orbit bumps and even accumulator lattice functions.

2 MULTITURN INJECTION INTO TRANSVERSE SPACE

For the present study, the aim for transverse space is to inject 15 to 20 turns of a beam of singly charged bismuth ions, at 400 mA peak current and $4\pi\mu$m.rad emittance, into an emittance of $50\pi\mu$m.rad in each phase plane. Analysis using an optimising computer code suggests that this can be achieved using an electrostatic septum tilted at an angle $\theta(\sim 60°)$ to the horizontal, which allows both planes to be filled simultaneously. Loss of particles from the circulating beam at the septum is minimised with the correct choice of machine tunes, Q_x and Q_y, allied with the varying closed orbit parameters, x_o, x'_o, y_o and y'_o, at the injection point. Optimum filling of phase space is achieved if the equations

$$\frac{\alpha_{ix}}{\beta_{ix}} = \frac{\alpha_{mx}}{\beta_{mx}} = -\frac{x'_i - x'_o}{x_i - x_o} \tag{1}$$

$$\frac{\alpha_{iy}}{\beta_{iy}} = \frac{\alpha_{my}}{\beta_{my}} = -\frac{y'_i - y'_o}{y_i - y_o} \tag{2}$$

hold, where the subscripts i and m refer to the incoming turn and the accumulator respectively. The injected emittances are then mapped into upright ellipses in the accepting machine's normalised phase space.

Two schemes may be envisaged. In the first, the accumulator parameters, $\beta_{mx}, \alpha_{mx}, \beta_{my}$ and α_{my}, are held constant and only the closed orbit bump varied during injection. Discounting space charge effects, the maximum number of turns that may be injected into the machine without particle loss turns out to be 15 (see table 1). For this model, $Q_x = 8.67, Q_y = 8.78$ and $\theta = 58°$. In the second scheme, the accumulator parameters are varied in such a way that the ratios (1) and (2) are held constant. Little is gained theoretically by varying x_i, x'_i, y_i and y'_i, which would in any case be difficult practically, and x'_o and y'_o are therefore determined directly by x_o and y_o. It is then possible to inject up to 20 turns with $Q_x = 8.62, Q_y = 8.91$ and $\theta = 52.8°$.

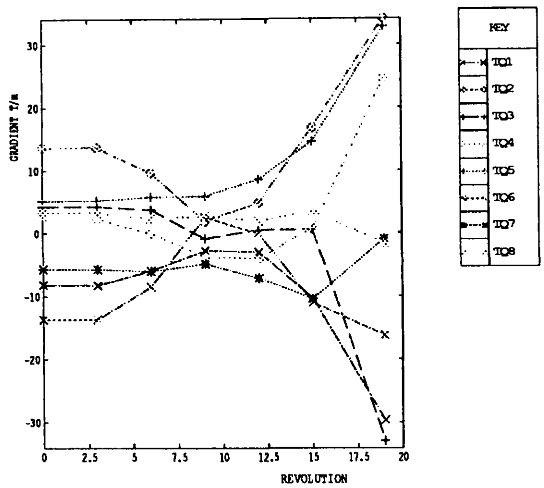

Figure 2: Trim quadrupole gradients for variable–β model

The optimum model has β_{mx} rising from 4.5 at the start of injection to 8.9 at the end, and β_{my} varying from 5.0 to 8.6 after 7 turns before returning to 5.0 at the end. The closed orbit bump typically falls by 12 mm horizontally but, because of the variation in β_{my}, changes by only 2 mm vertically. Phase space filling ranges from approximately 20 to $50\pi\mu$m.rad horizontally and 38 to $50\pi\mu$m.rad vertically. The vertical phase plane in particular tends to be hollow (see figure 5).

Turns	Loss %	
	fixed β	variable β
≤ 15	0.0	0.0
20	9.94	0.0
25	27.7	5.9
30	42.8	15.5
35	53.1	24.1
40	59.5	31.2
50	69.7	47.1

Table 1. Minimum beam loss for a range of injection turns

Although schemes may be found in which one or two additional turns may be injected without beam loss, in each case the optimised fractional tunes are unsuitable. For the HIDIF scenario under study [1], the values $Q_x = 8.67, Q_y = 8.78$ lie just below the resonance $2Q_y - Q_x = 9$ where there is a reasonable working space. Injection would be into several accumulator rings of the type shown in figure 1. This has superperiodicity 3, which is a design relatively unaffected by instabilities and resonances. The necessary variations in β_{mx} and β_{my}, subject to (1) and (2) and constant tunes, are achieved by means of 8 trim quadrupoles in the injection straight (shown enlarged). The gradients of these quadrupoles (figure 2) are higher than one would prefer and are an obvious drawback of the scheme. However, table 1 highlights the greater possibilities for injection afforded by the variable–β approach, and, since injecting sufficient beam into the required emittance is a major problem, it is likely that further study will concentrate on this method for the immediate future.

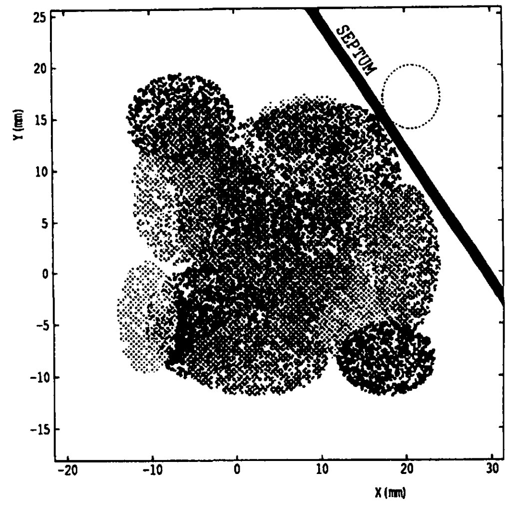

Figure 3: Transverse beam cross section at the end of injection

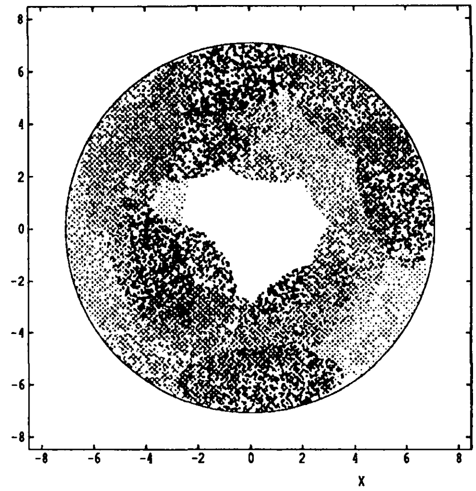

Figure 4: Normalised horizontal phase space at the end of injection

For the 20-turn variable–β model, the beam distribution at the septum in the absence of space charge effects, immediately after the final turn, is shown in figure 3. Figures 4 and 5 show the corresponding projections into each of the normalised phase planes.

The absence of losses in the HIDIF ring, taking into account a likely momentum spread of $\Delta p/p = 2 \times 10^{-4}$ in the linac beam, has been confirmed using the computer tracking code, TRACK2D. This is a development of the code used in an earlier analysis of an optimised injection scheme for HIF, described in [2] and [3]. With space charge taken into account, the tune is depressed by 0.05–0.1, and the recirculating beam will hit the septum unless the closed orbit scheme is revised. Losses of up to 20% are indicated, based on the same machine parameters. The hollowness in both phase planes is no longer evident and the emittances are increased as individual turns change their alignment. Nevertheless 97% of the remaining beam is within the re-

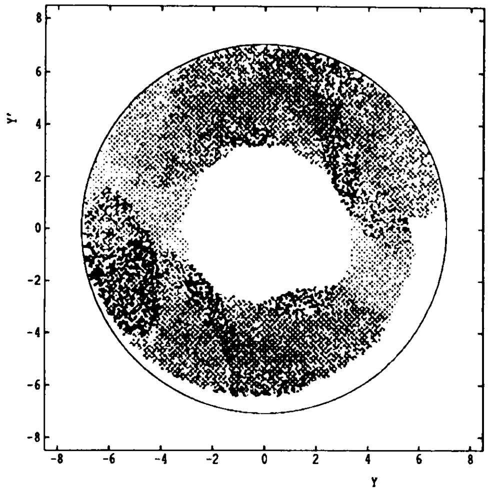

Figure 5: Normalised vertical phase space at the end of injection

quired emittances of $50\pi\mu$m.rad, so the halo generated appears quite sparse.

The closed orbit bumps, however, do need to be re-optimised under space charge effects and the indications are that the order of 15–17 turns may conceivably be injected without beam loss by this method. By comparison, the 15-turn fixed–β scheme gives losses under space charge of 16%, suggesting 10–12 lossless turns at best when optimised.

3 ADDITIONAL STACKING IN MOMENTUM SPACE

In view of the limits on the number of turns that may be injected into transverse space, schemes combining betatron stacking with energy ramping and/or RF manipulations have also been investigated. Such schemes have been studied for charge exchange injection in Hadron Facilities like KAON at TRIUMF [4] and, with normal injection (as considered here), for heavy ion accumulation in LEAR [5] in the context of the LHC programme. The basic principle is simple: the injection septum is at a place where the normalised dispersion $D_x/\sqrt{\beta_x}$ assumes reasonably large values $\simeq 5\ m^{1/2}$. While the orbit bump removes the circulating beam from the septum, the energy of the incoming linac beam is ramped such that its closed orbit, due to dispersion, remains close to the septum. In the HIDIF scenario this process was imagined as discrete: two or three batches differing by $(\Delta p/p)_{ramp}$ are injected, each one with the optimised procedure of section 2. The amount of this momentum difference is given by

$$\frac{1}{D_x}\left(\frac{2a_x - x + S_x}{\sin\theta} + \Delta x_0\right)$$

where $a_x = \sqrt{\epsilon_{ix}\beta_{ix}}$, S_x is the septum thickness and Δx_0 is the variation of the horizontal bump amplitude during the injection. Both terms are of the order 5×10^{-4}, while the half height of the linac microbunches is now assumed to be 2.5×10^{-4}. After completion of the injection, one is left with two or three ribbons in momentum space. If one injects into stationary buckets at the linac bunch frequency - one RF system per momentum batch - one can merge these ribbons by techniques used in the antiproton production process at CERN [6]. These RF systems also preserve the 400 ns macrobunch structure in the storage rings, in contrast to the barrier bucket system foreseen in the present scenario [1].

However, the scheme, which originally seemed promising, lost its attraction with the development of the estimated parameters of the injected beam: the linac bunch frequency doubled to 216 MHz, the full momentum height increased from 2.5×10^{-4} to 5×10^{-4} and the bunch length from 1.6 ns to 3 ns. In parallel, the target requirements have evolved from 10 ns to 5 ns pulse length; the tolerated momentum spread is still of the order of 10^{-2}. The consequence is simply that there is no space left for stacking in momentum space. In any case, the scheme has to handle the increased space charge forces (keeping the microbunch structure introduces a microbunching factor of order 0.45) and the tune variation between momentum batches due to chromaticity.

4 CONCLUSIONS

The analysis therefore indicates that, for the HIDIF study, RF stacking in momentum space is not promising and the optimal way of injecting sufficient beam is to use a tilted septum and vary the closed orbit and the accumulator lattice functions in both planes. Further study with particle tracking codes should indicate if the method remains feasible when the orbit bumps are optimised under the effects of space charge.

5 REFERENCES

[1] I. Hofmann: *Inertial Fusion with Accelerators.* Proceedings of the Fifth European Particle Accelerator Conference, Barcelona, 1996.

[2] C.R. Prior: *Multiturn Injection for Heavy Ion Fusion.* Proceedings of the Symposium on Accelerator Aspects of Heavy Ion Fusion, GSI, Darmstadt, March 1982, p. 290.

[3] C.R. Prior: *Particle Tracking in Solenoid Channels.* AIP Conference Proceedings of the International Symposium on Heavy Ion Fusion, Washington, DC, 1986, p. 302.

[4] D. Raparia, C.W. Planner, G.H. Mackenzie and J.R. Richardson: *Efficient Capture in an Accumulator of 20,000 Turns of Beam Injected from TRIUMF.* Proceedings of the 1985 Particle Accelerator Conference, Vancouver, IEEE Trans. Nucl. Sci. NS-32, 1985, p. 2456 .

[5] S. Maury and D. Möhl: *Combined Longitudinal and Transverse Multiturn Injection in a Heavy Ion Accumulator Ring,* Internal Note CERN PS/AR/Note 94-12, 1994

[6] D. Boussard and Y. Mizumachi: *Production of Beams with High Line Density by Azimuthal Combination of Bunches in a Synchrotron.* Proc. of the 1979 Particle Accelerator Conference, San Francisco, IEEE Trans. Nucl. Sci. NS-26, 1979, p. 3623.